9th Spacecraft Charging Technology Conference, April 2005, Tsukuba, Japan.

Potential Barrier in the Electrostatic Sheath Around Geotail, Cluster and BepiColombo spacecraft

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Abstract

In this paper, a fully self-consistent model of the plasma around an electron emitting central body in a spherically symmetric geometry is applied to analyse the electrostatic sheath around magnetospheric spacecraft in low density plasma. For all the case studied, it is shown that non-monotonic potential with negative potential barrier can exist. The magnitude and the location of the potential barrier in regions of the magnetosphere with large Debye length plasma are discussed.

1. Introduction

Outside the ionosphere, the photoemission current density is much higher than the current density of the ambient charged species. As a consequence, it significantly drives the floating electrostatic potential of sunlit surfaces to more positive values than the ambient plasma potential. Electrostatic potentials as high as a few tens of Volts positive have been observed [Pedersen et al. 1984]. To reduce such a high positive voltage ion emitters may be used [Torkar et al., 2001]. However, the photo-electrons may then leave the spacecraft surface more easily and their space charge may create negative potential barriers [Guernsey and Fu, 1970; Whipple, 1976; Zhao et al., 2000]. In this paper the appearance of barriers around electrostatic spacecraft is studied in 3 cases: Geotail, Cluster and BepiColombo.

2. Method

The method used in this paper is described in Thiébault et al. [2004]. It was derived from the approach elaborated by Parrot et al. [1982] and called the turning point method. According to this method, numerical stationary solutions of the Poisson-Vlasov system:

$$\Delta_R \Phi(R) = -\frac{\rho(R)}{\epsilon_0}$$

$$V_i.\nabla f_i - q_i \nabla\Phi.\nabla_p f_i = 0$$

where Φ is the electrostatic potential, R the radial distance, Δ_R is the Laplacian in spherical coordinate for spherical symmetry, ρ is the charge density, f_i is the density probability distribution function of species i, are found under the hypothesis that there is a spherical symmetry of the system. Thiébault et al. [2004] have shown that such solutions may be good approximations of the barrier potential profiles perpendicular to a spherical conductive and uniform spacecraft illuminated on one side provided that the collisions between particles and the magnetic field effects can be discarded. The other approximations are that the ambient plasma far away from the body and the photo-electron distribution at its source were assumed to be Maxwellian. The turning point method is briefly described below.

The turning point method is based on the analysis of the possible particles orbits using the turning point formulation to simplify and solve the Vlasov equation of the distribution function in a given potential.

Each number density

$$N_i(R) = \iiint f_i(R,V) d^3 V_i$$

where V_i is the velocity, is calculated as a function of the radial distance and the potential distribution via the identification of the domain of accessibility in function of momentum l and energy ? using the orbit classification shown on Figure1.

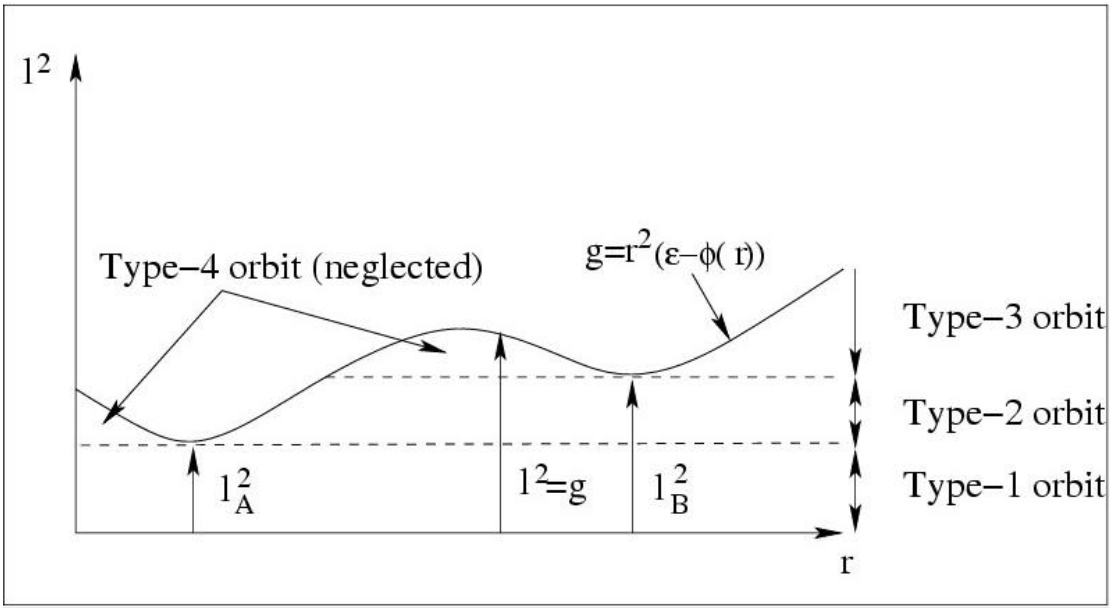

Figure 1: Example of domains of integration in l_i for given potential profile and location for attracted particles from ambient plasma.

It is then straightforward to obtain for the normalised density

$$n_i(r) = \frac{N_i(r)}{N_i^S}$$

the following dimensionless expressions:

$$n_i(r) = \frac{2\alpha_i \cdot \exp(\phi_{i,S})}{\sqrt{\pi}} \int_{\phi_{i,S}}^{\infty} \exp(-\epsilon_i) M_{n_i}(\epsilon_i) d\epsilon_i$$

$$\text{where} \qquad M_{n_i}(\epsilon_i) = \sum_j \xi_j \left[K_{n_i}(l_i^2)\right]_{(l_i^2)_{\min_j}}^{(l_i^2)_{\max_j}}$$

$$\text{with} \qquad K_{n_i}(l_i^2) = \frac{1}{2r}\sqrt{g_i(r) - l_i^2}$$

$$\text{and} \qquad g_i(r) = r^2(\epsilon_i - \phi_i).$$

Once the density of each species is known, the total electric charge can be derived and injected it in the Poisson equation, which is solved via a standard numerical scheme, e.g., Gauss-Seidel in one dimension. The solution to the Poisson-Vlasov system is then found iteratively using over-relaxation.

Three examples of solutions from Thiébault et al. [2004] are shown on Figure 2 (dashed lines) in the case of a sphere using the input parameters listed in Table 1 for three different values of the potential.

Table: 1 Parameters for the curves of Figure 1

Parameter	Value
Electron and ion temperature	1.0 eV
Photo-electron temperature	2.5 eV
Photo-electron current density	50 $\mu A.m^{-2}$
Plasma number density	100 cm^{-3}
Debye length	0.74 m
Spacecraft potential	-1.0, 0.0 and +1.0 V
Spacecraft radius	1.0 m

It must be noted that the photo-electron current density indicated in Table 1 is the one corresponding to the photo-emission of an half-illuminated sphere. In practice, the simulation is performed on a symmetric sphere with a current density such that the total current is unchanged.

The other curves on Figure 1 correspond to the potential profile obtained through PIC simulations of the plasma distribution around the sphere using the PicUp3D software [10, Thiébault et al. 2005]. It can be seen that the model based on the turning point method and the curves derived from the PIC simulation are in a relatively good agreement (within a few 0.01 k_BT_e/q_e).

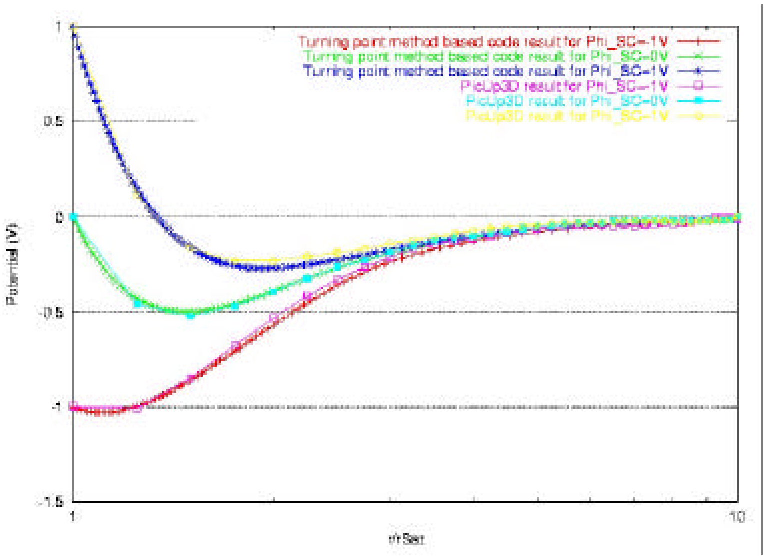

Figure 2: Potential profiles obtained with the turning point method and via PIC simulations for inputs parameters of Table 1.

3. Geotail spacecraft

The Geotail mission is a Japanese-US spacecraft designed to operate in the distant geomagnetic tail and equipped with an ion emitter to actively control the spacecraft potential [Schmidt et al. 1995].
Zhao et al [1996] have used the current balance equation derived from simplified formulas of the current density resulting to induce the existence of a potential barrier. Their results of the estimate of the potential barrier as a function of the spacecraft potential is shown in Figure 3 for typical plasma and spacecraft parameters indicated in Table 2. The results obtained with the turning point method under the same set of hypotheses as used by Zhao et al. for the spacecraft and environment model are also shown on Figure 3.

Table: 2 Parameters for Geotail spacecraft simulations

Parameter	Value
Electron and ion temperature	100 eV
Photo-electron temperature	1.5 eV
Photo-electron current density	50 $\mu A.m^{-2}$
Plasma number density	1.0 cm^{-3}
Debye length	74 m
Spacecraft potential	0.0 to 7.0 V
Spacecraft radius	1.1 m

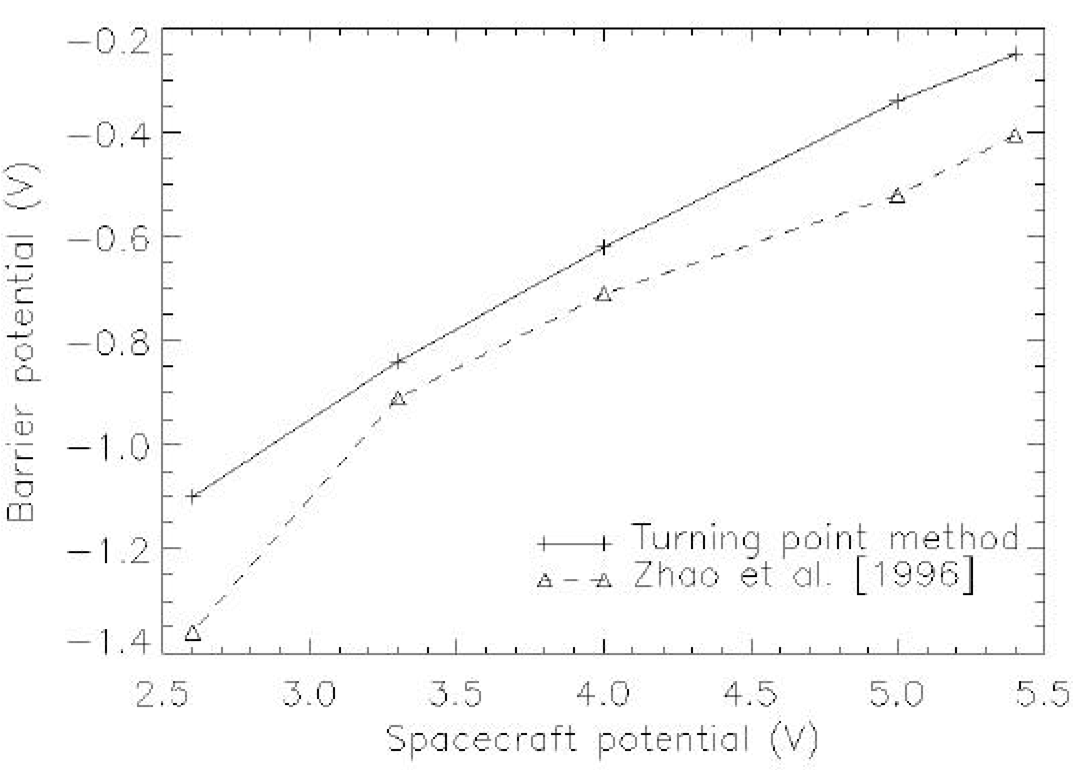

Figure 3: Minimum potential deduced from Geotail observation and computed by the turning point method as a function of the spacecraft potential.

One can see that the potential profile computed by the two methods have the same shapes but differ by a constant value. It can be shown that the derivation of Zhao et al. is actually undetermined within a constant value [Thiébault et al., 2004]. We therefore conclude that our results on the potential are consistent with the ones of Zhao et al. The difference between the barrier locations is more significant. It was explained by Zhao et al., that their assessment of the location of the barrier may be strongly depending on the actual hypothesis they have made for the a priori and arbitrary shape of the barrier. Our results confirm this fact and suggest that the barrier location is actually closer to the spacecraft and its distance from the spacecraft decreases with decreasing potential unlike predicted by Zhao et al. [7].

4. Cluster spacecraft

The European Space Agency Cluster mission is constituted of 4 spacecraft on a high inclination elliptical orbit (perigee: 19,000 km, apogee: 119,000 km) designed to explore magnetospheric and solar wind interaction processes. It is equipped with an ion emitter, similar to the Geotail one, to actively control the spacecraft potential in the magnetospheric lobe regions. In these regions, the ion emitter is routinely operated with a current of a few tens of μA and the spacecraft voltage falls in the range of a few Volts (compared to a few tens of Volts if the ion emitter were switched off). The spacecraft hub has a cylindrical shape with height 1.3 m and radius 1.45 m. To investigate the expected potential barrier characteristics, simulations have been performed for a conductive sphere with a surface equal to the one of the cylinder and hence with a radius of 1.41 meter. The characteristics of the model used are given in

Table 3. It must be noted that the barrier characteristics are given for a spacecraft potential as low as 0 V although this lower bound is likely to be beyond the capability of the ion emitter in this type of plasma environment.

The plot of the predicted values of the potential barrier and the location of its minimum is shown on Figure 4 as a function of the spacecraft potential. It can be seen that the value of the potential barrier can be as low as -2 V when the spacecraft potential is null and is decreasing rather rapidly toward zero for increasing value of the spacecraft potential. It is predicted that no more potential barriers exist for a spacecraft potential above 7 V under the simulation hypotheses.
Also it can be noted that the potential barrier minimum location varies very much for a small variation of the spacecraft potential.

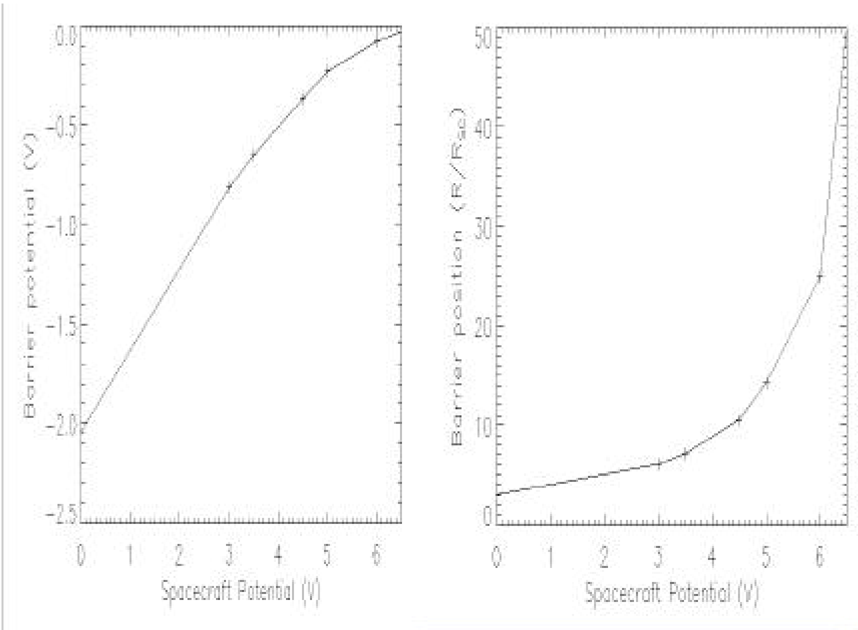

Figure 4: Potential barrier height F_B (left panel) and location (right panel) versus Cluster spacecraft potential computed with the turning point method for Table 3 simulation parameters.

Table: 3 Parameters for Cluster spacecraft simulations

Parameter	Value
Electron and ion temperature	100 eV
Photo-electron temperature	1.5 eV
Photo-electron current density	30 μA m^{-2}
Plasma number density	1.0 cm^{-3}
Debye length	74 m
Spacecraft potential	0.0 to 7.0 V
Spacecraft radius	1.41 m

<u>BepiColombo Spacecraft</u>

The BepiColombo mission is a joint ESA-JAXA mission that consists of 2 spacecraft to be launched in 2012 to explore the planet Mercury: (1) a planetary orbiter (400x1500km polar orbit, 3-axis stabilised) and a magnetospheric satellite

(400x12000km polar orbit, spinning 15rpm). Because Mercury has no atmosphere, the plasma density in the Herman magnetosphere can be very low (0.1 cm-3 or even less). The photo-emission which is expected to be as high as 10 times the typical photo-emission at 1 AU. Very few reliable data exist on the environment hypothetical values (listed in Table 4) have been used for the modelling. Simulations using data from Table 4 are shown in Figure 5. It can be seen that despite the much higher photo-electron current density the barrier is only slightly larger than for the case of spacecraft in the Earth magnetopshere.

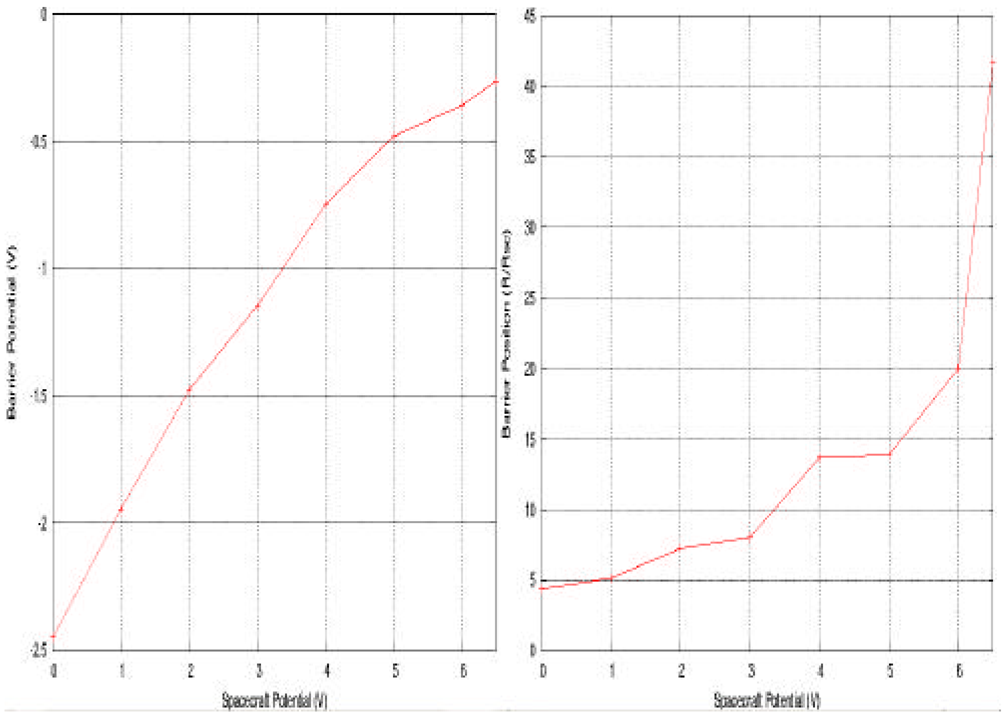

Figure 5: Potential barrier height Φ_B (panel a) and location (panel b) versus BepiColombo magnetospheric spacecraft potential computed with the turning point method for Table 3 simulation parameters.

Table: 4 Parameters for BepiColombo spacecraft simulations

Parameter	Value
Electron and ion temperature	100 eV
Photo-electron temperature	1.5 eV [checked]
Photo-electron current density	200 μA.m^{-2}
Plasma number density	0.1 cm-3
Debye length	74 m
Spacecraft potential	0.0 to 6.5 V
Spacecraft radius	0.43 m

Conclusion

It has been shown that potential barriers are expected to occur around spacecraft in low density of magnetospheres. Such low density values are observed typically in the magnetospheric lobes and in the Hermean magnetosphere. An interesting finding is that despite the much higher photo-electron current density expected in the Hermean magnetosphere the barrier is predicted to be only slightly larger than for the case of spacecraft in the Earth magnetosphere. This will have to be investigated further in the future.

Acknowledgments

This study has been performed in the frame of the Spacecraft Plasma Interaction Network in Europe (SPINE) activities (cf. www.spis.org). We acknowledge useful discussions with the participants of the 5th SPINE workshop.

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